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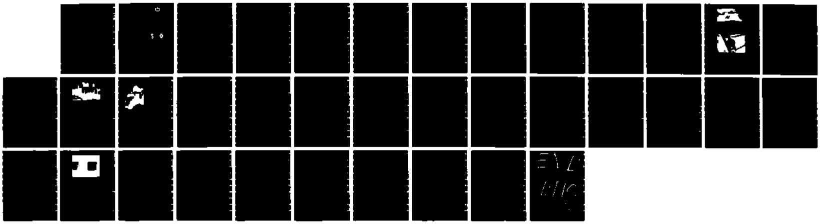

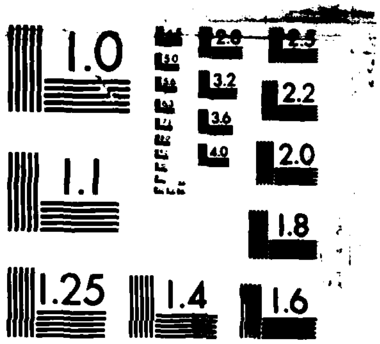

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Special Report 82-29

December 1982

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Cold weather construction materials

Part 2: Field validation of laboratory tests on regulated-set cement for cold weather concreting

B.J. Houston, G.C. Hoff and F.H. Sayles

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The Army carries on construction projects in localities where the concrete placing season is shortened considerably by the cold climate. This study evaluates "regulated-set" cement, which is a fast setting, rapid strength gain cement, that appeared to have great promise and would allow concrete to be placed at ambient temperatures as low as 15°F. Both mortars and concretes made with regulated-set cement were studied in the laboratory with favorable results, so the laboratory results were validated with field testing. Two 12-ft by 12-ft by 8-in. test slabs were cast in January 1975 when the mean ambient temperature was approxi-

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20. Abstract (cont'd)

mately 15°F. The only differences in the two slabs were the concrete mixture temperature and air entrainment. The slabs received no special protection from the ambient temperatures. Neither slab obtained any appreciable compressive strength at 1 day but slab 1 had approximately 1200 and 2000 psi at 7 and 28 days, respectively, while slab 2 had 2200 and 3300 psi, respectively. The concrete in both slabs was wetter than intended. Since there was no strength gain at day 1, whereas there had been in laboratory tests of approximately the same concrete mixture but with an earlier shipment of regulated-set cement, a sample of the cement from the field test was brought to the laboratory for comparison with the cement used in the laboratory tests. Chemical and physical tests indicated that there was a difference in chemical composition; the laboratory shipment had a higher sulfate content. This difference points out the need for a responsive purchase specification, which is presently not available. Keywords: Cold regions, Regulated set concrete.

PREFACE

This report was prepared by B.J. Houston, former Research Civil Engineer and G.C. Hoff, Research Civil Engineer, Materials and Concrete Analysis Group, Concrete Technology Division, U.S. Army Engineer Waterways Experiment Station (WES); and F.H. Sayles, former Research Civil Engineer, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided under DA Project 4A762719AT06, Military Construction and Maintenance in Cold Regions; Task 02, Cold Regions Building Systems for Military Installations; Work Unit 001, Evaluation of Innovative Concepts for Structures and Materials in Cold Regions. This study was authorized by Intra-Army Orders No. CRREL 75-18 (23 October 1974) and No. CRREL 75-27 (24 December 1974) and is the second report of a series.

The work reported here was conducted at WES in Vicksburg, Mississippi, and at CRREL, under the direction of B. Mather, J.M. Scanlon, G.C. Hoff, B.J. Houston and F.H. Sayles. This report was technically reviewed by R. Johnson, formerly of CRREL.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To obtain
inches	25.4	millimetres
feet	0.3048	metres
square feet	0.09290304	square metres
pounds (mass)	0.4535924	kilograms
cubic yards	0.7645549	cubic metres
degrees Fahrenheit	$t_{°C} = (t_{°F}-32)/1.8$	degrees Celsius
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic foot	0.59327638	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals

COLD WEATHER CONSTRUCTION MATERIALS

Part 2

Field Evaluation of Laboratory Tests on Regulated-Set Cement for Cold Weather Concreting

by

B.J. Houston, G.C. Hoff and F.H. Sayles

INTRODUCTION

The Army carries on construction projects in many places of varying climates. In many areas, the construction season is shortened considerably by the advent of extended periods of cold weather. The problems and proposed solutions associated with mixing, placing and curing concrete in cold weather are well known and documented but a permanent, universal solution has not been found. In arctic and subarctic areas, concrete must frequently be placed at temperatures near and below freezing. Especially in the Arctic, the placing of concrete at temperatures below 0°C is generally not practicable, except for small projects where external heat can be applied or for extremely large-scale operations with sizable concrete plants (whose large quantity of heat of hydration maintains the concrete temperature above freezing). Concrete can thus be placed only during a short work season averaging 1 to 2 months in the Arctic and 2 to 3 months in subarctic areas. The minimum practicable temperature limit for concreting, as viewed by various countries with long periods of cold weather, varied from 23°F in Denmark to -4°F in Sweden.

An investigation was conducted in 1973 and 1974 at the U.S. Army Engineer Waterways Experiment Station (WES) to evaluate the use of regulated-set cement in concrete for cold weather construction. The results of these tests were reported in Part 1 of this series (Houston and Hoff 1975). These tests indicated that concrete made with regulated-set cement mixed at above-freezing temperatures would begin hydration within a few minutes, even when placed at subfreezing temperatures, and would sustain hydration by chemical heat generation long enough for sufficient strength to develop to resist initial freezing damage.

The overall objective of this program is the evaluation of existing and new binder materials that could be used in concrete and concrete-like composites in cold weather environments. These materials should be placeable in the field at temperatures as low as 15°F, and should require a minimum of attention after placement. The specific objective of the portion of the program reported here was the field validation of laboratory tests of regulated-set cement used as a binder for concrete that is to be placed at low temperatures.

The work was accomplished in two phases. Phase I was an attempt to synthesize the field experience of various agencies, organizations and individuals that used regulated-set cement. Phase II was an evaluation of prototype concrete slabs cast and cured at 15°F and below. Two concrete slabs containing regulated-set cement were cast at low temperatures in the field to validate laboratory test results and to evaluate casting procedures and equipment.

SYNTHESIS OF FIELD EXPERIENCE

Regulated-set cement has been used for a number of years in nonmilitary construction for highway patches, slipform tunnel liners and cast-in-place roof decking. Letters requesting information (construction problems, cracking, durability, cost, etc.) on such uses were written to Corps of Engineers districts, cement producers, the Portland Cement Association, construction companies and others who may have had experience with regulated-set cement.

The response to the inquiries was very disappointing. In almost all cases, the people contacted could not or did not provide any documentation of their efforts, hence very little usable information was received. Only one of the Corps of Engineers districts or divisions reported any use of regulated-set cement. The Missouri River Division Laboratory used it in some experimental shotcrete panels at Chatfield Dam in 1972. They used a mortar mix of 1 part cement to 3 parts sand by weight. Table 1 gives the results of a comparison of regulated-set cement and a number of set accelerators used at Chatfield Dam. These data indicate no significant advantage in using regulated-set cement instead of accelerators at above-freezing temperatures.

The Alaska District replied that market conditions in Alaska have not developed to the point where regulated-set cement is attractive to poten-

Table 1. Results of tests on shotcrete panels made at Chatfield Dam (Missouri River Division, Corps of Engineers).

Mix		Unit weight (lb/ft^3)	24-hr adsorption (%)	Compressive strength (psi) 7 hr	24 hr	8 day	28 day	90 day	1 yr
Control (job cement and mix)		143.7	8.1	Too	2240	5010	7360	8500	9560
		144.6	8.2	green	2340	5290	7470	8700	9260
		144.9	8.3	to saw*	2280	5840	7730	9690	9100
	avg	144.4	8.2		2290	5380	7520	8960	9310
3% Tricosal T-1		140.4	9.4	1200	2030	3210	4510	6200	6680
		141.9	9.7	1080	1840	3240	4590	6390	6110
		142.2	9.7	890	2100	3300	4700	6040	6090
	avg	141.5	9.7	1060	1900	3250	4600	6210	6290
3% Tricosal 211-Av		139.2	10.0	1120	1630	3240	4230	5460	6000
		140.9	10.1	1130	2100	3290	4360	5610	6260
		140.9	10.5	1130	1780	3310	4440	5530	5570
	avg	140.6	10.2	1130	1840	3280	4340	5530	5940
3% Sigunit		141.1	9.0	1370	1930	3500	4520	5840	6840
		141.7	9.0	1260	2050	3550	4600	6590	5500
		142.0	9.5	1590	2160	3580	4970	6040	6430
	avg	141.6	9.2	1410	2050	3540	4700	6160	6260
2% Calcium chloride		144.2	7.6	920	2890	5500	7730	9770	10,130
		144.5	8.0	1080	2880	5530	8100	9060	10,460
		145.3	8.1	1030	3180	5930	8220	9500	9,460
	avg	144.7	7.9	1010	2980	5650	8020	9440	10,020
3% Isocrete, extra P		141.6	9.7	Too	2750	3480	4870	4640	6680
		142.3	9.7	green	2940	3570	5130	6290	6200
		142.7	10.4	to saw*	2480	4000	5270	6120	5560
	avg	142.2	9.9		2720	3680	5090	5680	6150
3% Isocrete AZ		141.3	9.9	Too	2280	3860	4800	5680	6290
		141.7	10.3	green	2180	3920	4880	5830	6340
		142.2	10.4	to saw*	2180	3940	4910	5270	5830
	avg	141.7	10.2		2210	3910	4860	5590	6150
Regulated-set cement		142.7	8.7	1160	3050	4310	5420	6610	7270
		142.9	8.9	860	2470	4540	6400	8090	8020
		142.9	8.9	860	3400	5520	6800	7530	7590
	avg	142.8	8.8	960	2970	4790	6210	7410	7630

* Strength estimated below 600 psi.

tial users. This is primarily due to lack of experience, higher costs and potential difficulties. Bechtel Inc., in planning for the Alaska oil pipeline, had not seriously considered regulated-set cement but expected to accelerate setting where required with chemical admixtures.

PROTOTYPE EVALUATION

Two test slabs were constructed in January 1975 in an area adjacent to CRREL in Hanover, New Hampshire. This location was selected because it has low temperatures in January and CRREL was present to lend support. The

Figure 1. Forms for slabs 1 and 2. Push-out molds are in place prior to placing of concrete.

Figure 2. Plastic push-out cylinder molds.

slabs were 12- by 12-ft by 8-in. thick and were constructed with a sand subbase covered with polyethylene (Fig. 1).

Thermocouples were positioned in the center of the form at locations in the middle of each slab and also slightly above the top of the slab so that the temperatures of the concrete and the ambient air could be recorded during both placing and curing. Plastic push-out molds, as shown in

Figures 1 and 2, were placed in the form so that specimens that were cured in exactly the same manner as the test slabs could be evaluated. Use of these molds, if the strength of the concrete within them is representative of the in situ concrete, would eliminate the need for drilling test cores. However, test cores were also taken from the slabs for comparison. The results of the tests on the cylinders cast at the site, drilled cores and push-out cylinders are shown in Table A1.

Curing

The tops and sides of the concrete slabs were exposed to the ambient air temperatures (see Fig. 11 and 12) and the bottoms were exposed initially to the ground temperature (≈ 29°F). However, the ground temperature at a point 1/2 in. below the bottom of the concrete rose to 31°F within 2 hours. To reduce evaporation and sublimation from the surface of the slabs, a plastic sheet was placed over the top surfaces.

Concrete mixture

The mixture used in the field tests at CRREL was essentially the same as that used in the laboratory work at WES (Houston and Hoff 1975), with adjustments being made for the different aggregate used in the field mixture. This mixture had a compressive strength of approximately 3000 psi after 3 days under laboratory conditions. The fine and coarse aggregate used in the laboratory was limestone whereas the aggregate used in the concrete for the field tests at CRREL was a siliceous material (trap rock) from a local source. The physical properties of the trap rock are shown in Table 2.

There was 1.0% total moisture in the coarse aggregate as sampled at the batch plant and 4.4% in the sand. This was taken into account in adjusting the mixture proportions. The gradations of both the coarse and fine aggregate met the Federal Specifications for Concrete Aggregate presented in CRD-C 131-55 (WES 1949). Saturated surface-dry batch weights of the mixture used in the field tests are shown in Table 3. The slump, air content and temperature of the ingredients of the two mixtures are shown in Table 4.

The primary differences between the mixtures for slabs 1 and 2 were the air content, the slump and the temperature of the water. In slab 1 the

Table 2. Physical properties of trap rock used in concrete field-tested at CRREL.

	Coarse aggregate	Fine aggregate
Specific gravity	2.90	2.71
Absorption (%)	0.6	0.8
3/4 in.*	98**	100**
1/2 in.	54	100
3/8 in.	25	100
No. 4	5	100
No. 8	3	87
No. 16	0	63
No. 30	0	36
No. 50	0	15
No. 100	0	7
No. 200	0	6

* Sieve size
** Cumulative percent passing that sieve.

Table 3. Saturated surface-dry batch weights (lb) for 1 yd^3 of the concrete field-tested at CRREL.

Material	Weight
Cement (reg-set)	500
Fine aggregate	1289
Coarse aggregate (3/4 in. max)	1985
Water	265
Air-entraining agent	0.75

Table 4. Slump, air content and temperature of ingredients of concrete field-tested at CRREL prior to mixing (concrete strength samples were cast from the last of the concrete to be discharged from the mixer).

	Cement temp. (°F)	Fine aggregate temp. (°F)	Coarse aggregate temp. (°F)	Water temp. (°F)	Air temp. (°F)	Mixture temp. at discharge (°F)	Slump (in.)	Air content (%)
Slab 1	27*	32	30	54	23	32	8	13
Slab 2	28*	36	28	106	22	49	5-1/2	4

*Temperature in storage barrels in warehouse.

Figure 3. Mobile batching and mixing unit.

water temperature prior to batching was 54°F, giving a concrete temperature at discharge of 32°F, whereas the water added to the concrete in slab 2 was 106°F prior to batching, giving a concrete temperature at discharge of 49°F. The concrete was mixed in a 6-yd^3 mobile unit (Fig. 3) that has bins or tanks for cement, coarse aggregate, fine aggregate and water. The aggregate bins were charged at the batch plant by a front-end loader (Fig. 4), and the cement bin was loaded by hand from drums. The unit operates by opening bin gates a calibrated amount onto a screw auger that mixes the proportioned ingredients and either pumps or chutes the freshly mixed concrete into the form. It takes only a few minutes to produce 6 yd^3 of concrete.

The concrete used in each slab did not exactly meet the specifications of the experiment because the WES and CRREL personnel had little experience with the mobile batching equipment. Slumps were higher than desired for both slabs, thus indicating a higher water content in the concrete than desired. The air content of the mixture placed in slab 1 was too high because there was no opportunity to adjust the air-entraining admixture content in trial mixtures prior to actual placing of the concrete.

The setting of the concrete in both test slabs at CRREL was not as fast as the laboratory work indicated it would be. This could have been caused by a number of factors. As noted earlier, the mixtures were wetter

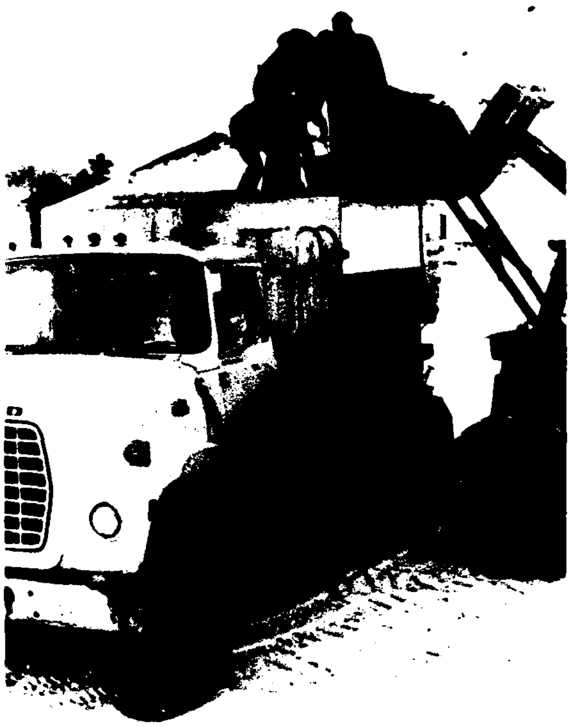

Figure 4. Charging aggregate bins with a front-end loader.

(higher slumps) and the air contents were higher than the mixture designed in the laboratory. Both of these factors would have extended setting times but neither should have delayed the setting time to the extent evidenced. It was also suspected that the shipment of regulated-set cement used in prototype evaluation at CRREL was somehow different from the cement used in the earlier work at WES, although both were from the same manufacturer. A sample of the cement used at CRREL was brought to the WES concrete laboratory for comparison with the earlier cement.

Tests conducted

The schedule for testing cylinders, cores and beams is shown in Table 5.

The locations of the push-out cylinders and test cores taken from the test slabs are shown in Figure 5. The results of the strength tests are shown in Table A1 and Figures 6 through 10. The strength data for the 6-in.-diam by 12-in.-long cylinders that were cast at the time of pouring and cured in a humid room at 70°F showed considerable scatter at 7 days, as

Table 5. Testing schedule for concrete slabs placed at CRREL.

Age (days)	Slab 1 Cast cyl 70*	Slab 1 Cast cyl 15	Slab 1 Core 15	Slab 1 Push-out 15	Slab 1 Beam 15	Slab 2 Cast cyl 70	Slab 2 Cast cyl 15	Slab 2 Core 15	Slab 2 Push-out 15	Slab 2 Beam 15
1	✓	✓		✓		✓	✓		✓	
7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14	✓	✓	✓	✓		✓	✓	✓	✓	
28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
60			✓					✓		
90	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

*Test temperatures (°F) of the various specimens.

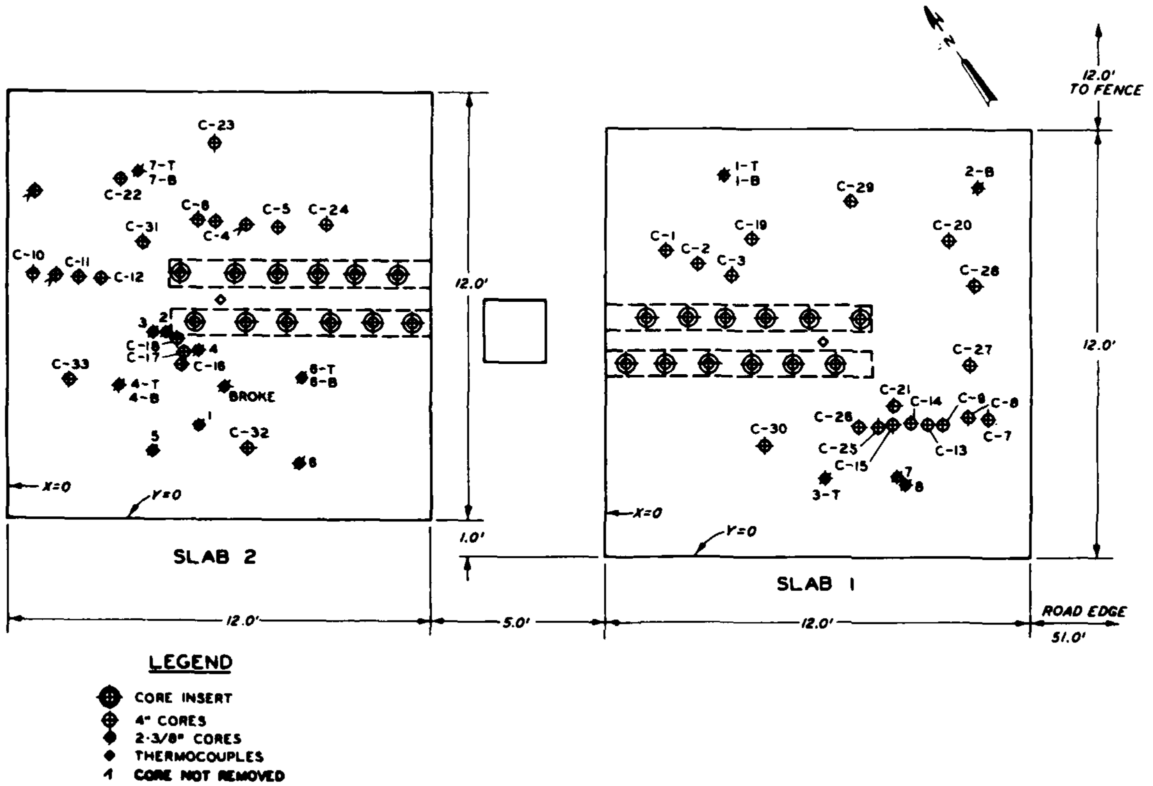

Figure 5. Location of test cylinders and cores taken from slabs 1 and 2.

shown in Figure 6. In Figure 7 the limited data indicate a decrease in strength at 28 days. It is not clear whether this decrease in strength is real or part of the scatter in the data; however, the latter explanation is most likely. In contrast, the cylinders cured in outside temperatures showed reasonably consistent increases in strength, but at lower values. These lower values are to be expected since these cylinders were frozen and

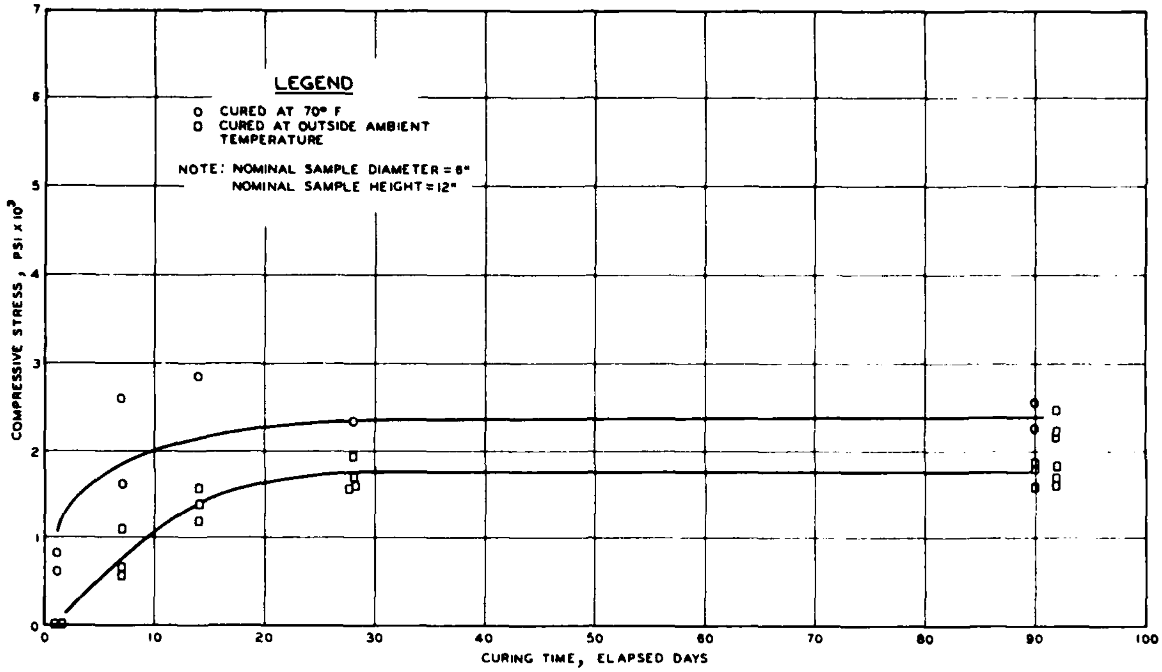

Figure 6. Compressive strength vs time for 6- by 12-in. test cylinders cast from concrete of slab 1 (see Fig. 11 for outside temperatures).

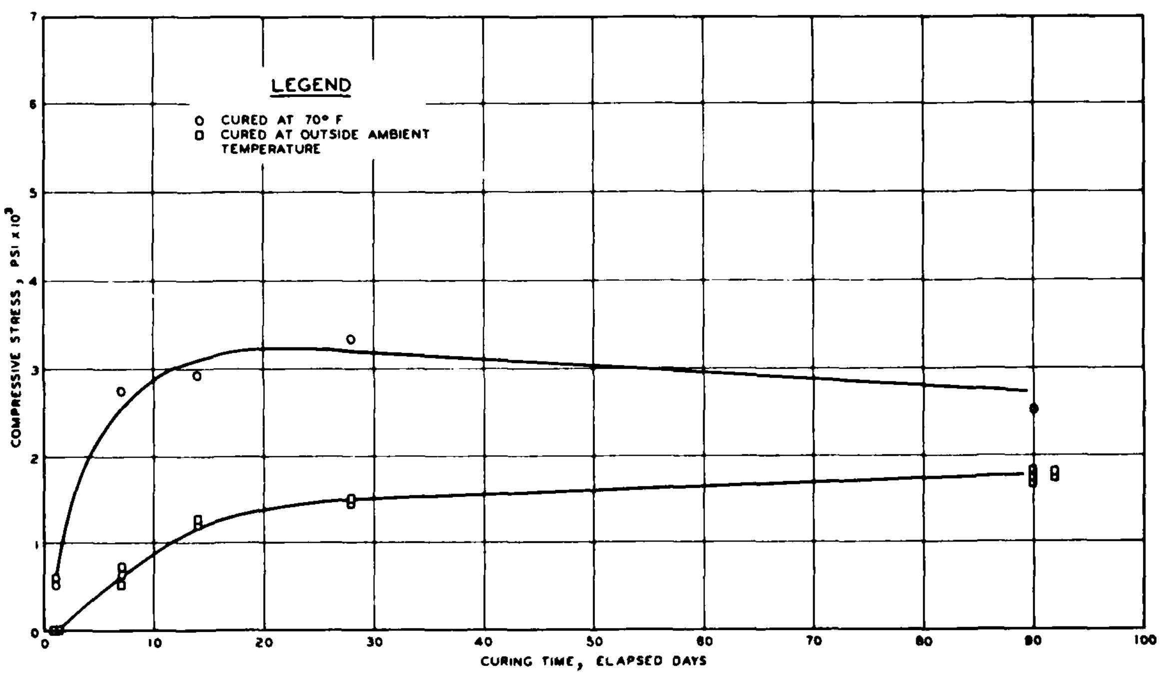

Figure 7. Compressive strength vs time for 6- by 12-in. test cylinders cast from concrete of slab 2 (see Fig. 12 for outside temperatures).

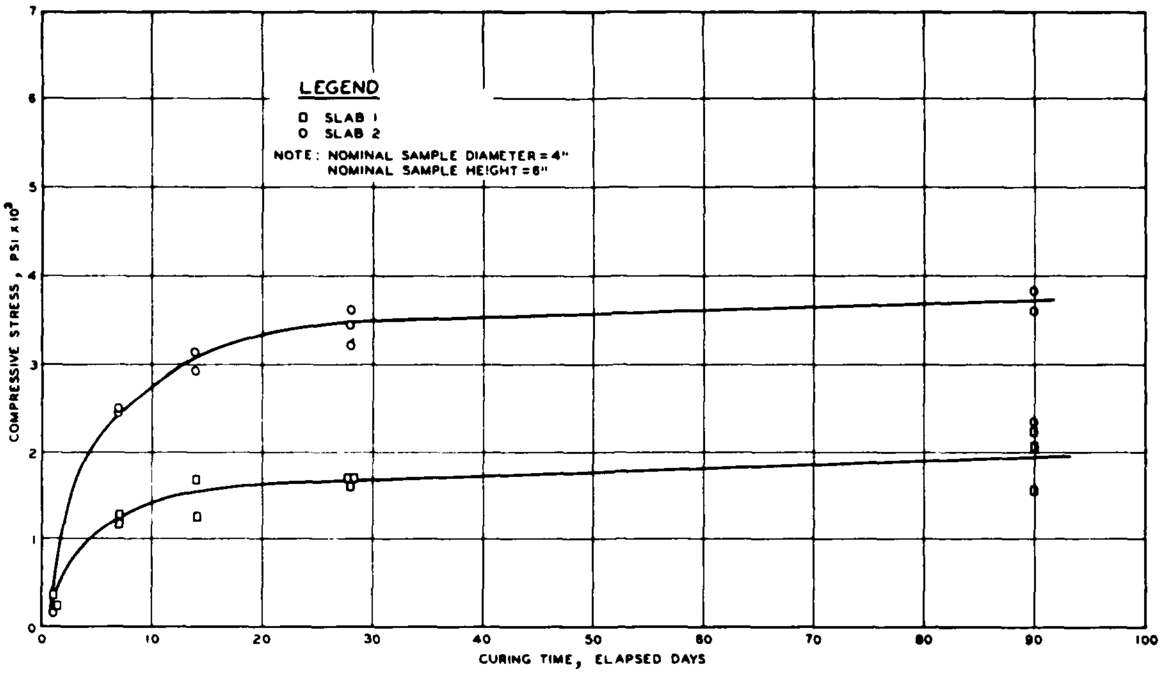

Figure 8. Compressive strength vs time for push-out cylinders cast from concrete of slabs 1 and 2 and cured in the slabs at outside ambient temperatures.

were subjected to the temperature variations shown in Figures 11 and 12 during their curing period.

The compressive strengths of the 4-in.-diam by 6-in.-long cylinders cast in the plastic push-out molds and cured in the slabs were reasonably repeatable (Fig. 8). The strengths of the push-out cylinders from slab 2 are almost twice those of the 6- by 12-in. cylinders from the same concrete pour but cured outside as individual cylinders without the benefit of the heat generated by the slab during hydration. The push-out cylinders from slab 1 had strengths similar to the 6- by 12-in. cast cylinder from this slab. (Compare curves in Figure 6 with those in Figure 8.) The temperature records in Figures 11 and 12 show that during the first few hours after placement the midpoint of slab 1 barely reached 38°F before cooling to below freezing. In contrast slab 2 started at a higher temperature (40°F) and during the first few hours after placement its temperature exceeded 54°F, thus providing enough heat during hydration to develop corresponding increases in strength. Since the cast cylinders had more surface area exposed to the outside air temperatures and relatively smaller masses than the slabs, the cylinders cooled quicker, resulting in a reduction in the strengths.

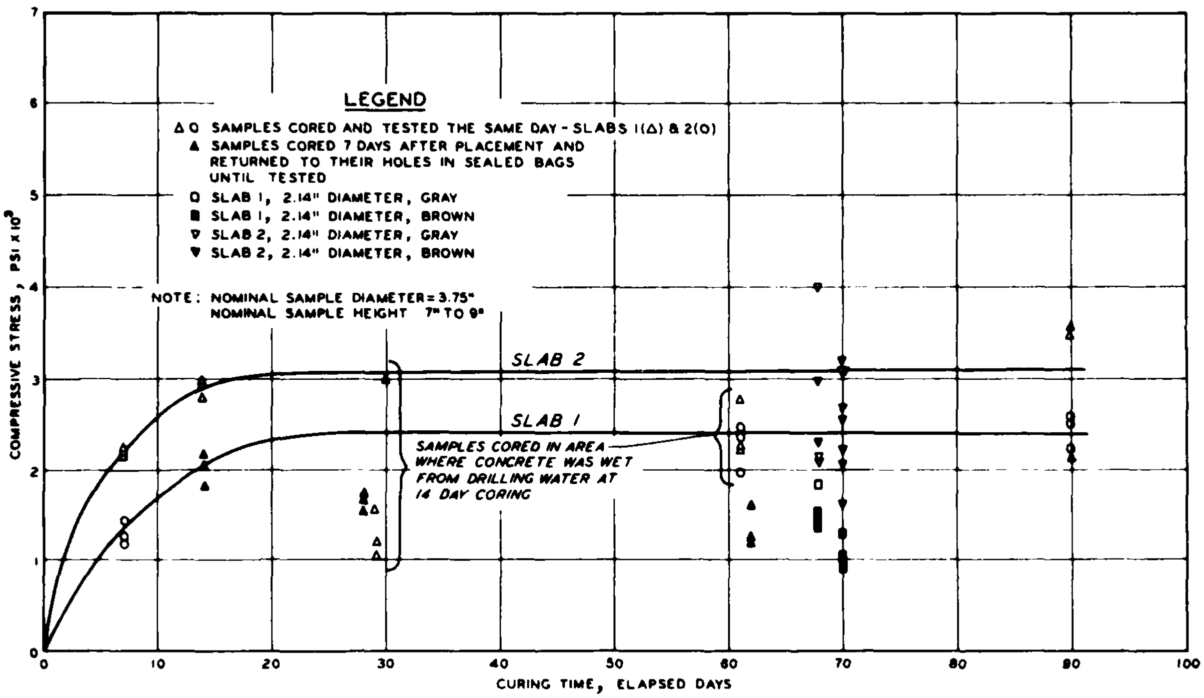

Figure 9. Compressive strength vs time for drilled cores from slabs 1 and 2 (gray and brown are concrete sample colors).

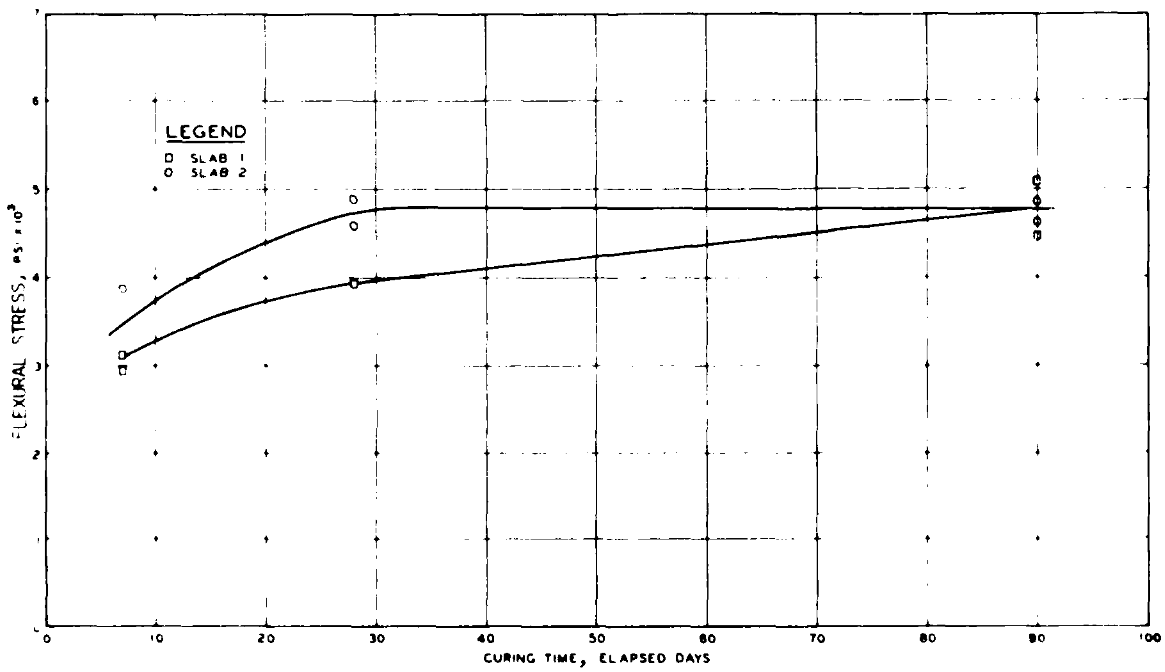

Figure 10. Flexural strength (third-point loading) vs time for beams cast from concrete of slabs 1 and 2 (6- by 6-in. by 3-ft-long beams were cured outside in air temperatures shown in Fig. 11 and 12).

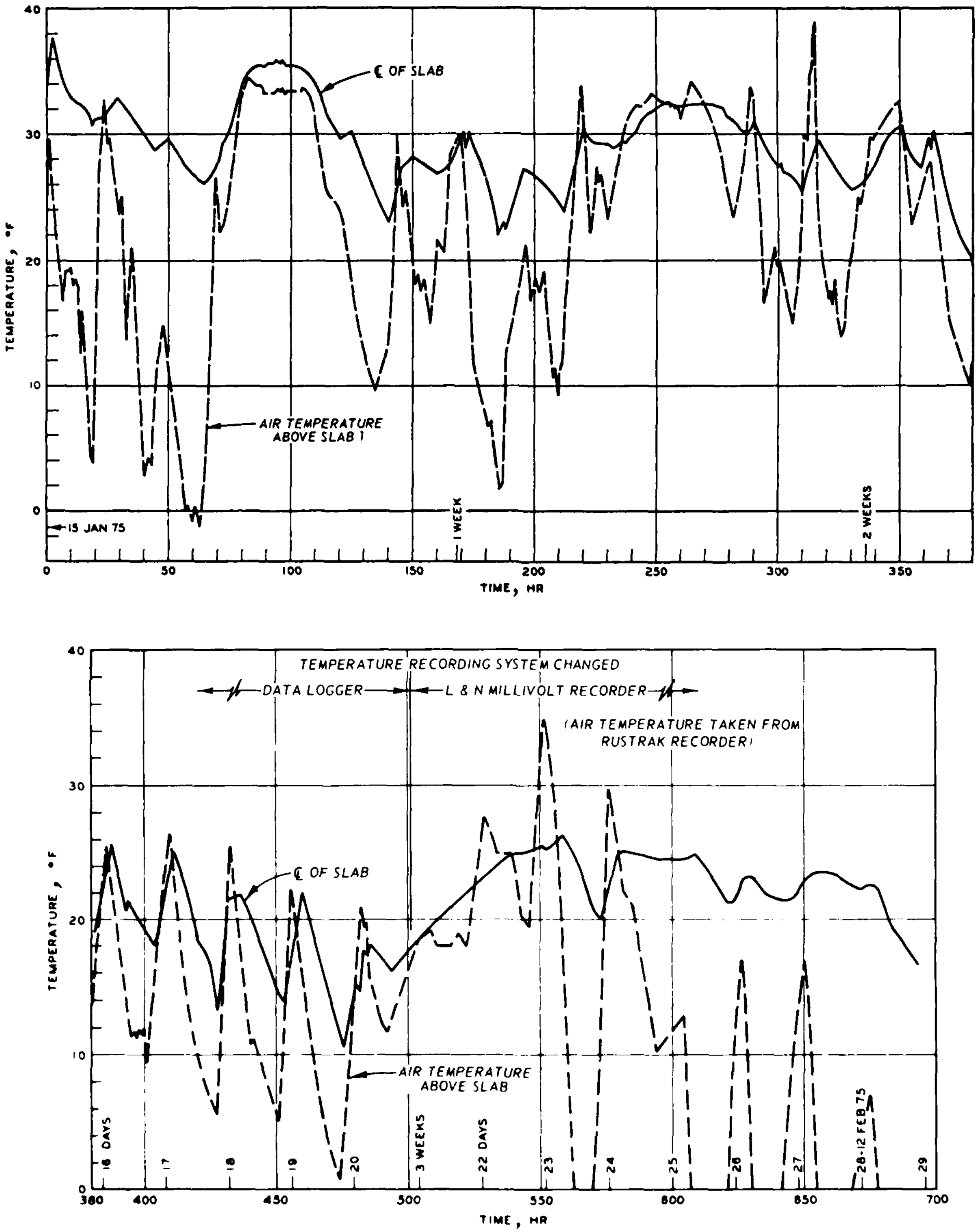

Figure 11. Temperature record of slab 1.

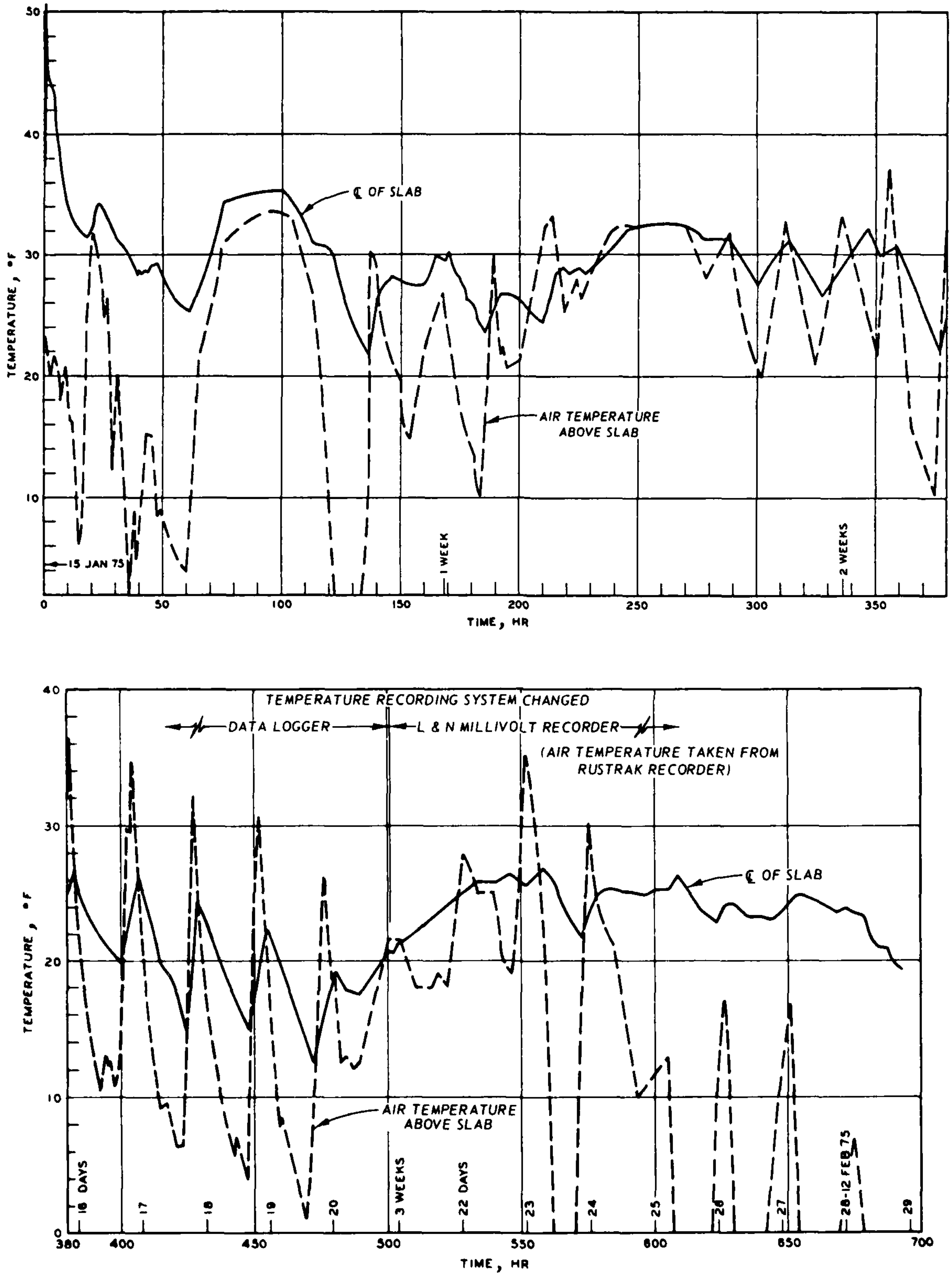

Figure 12. Temperature record of slab 2.

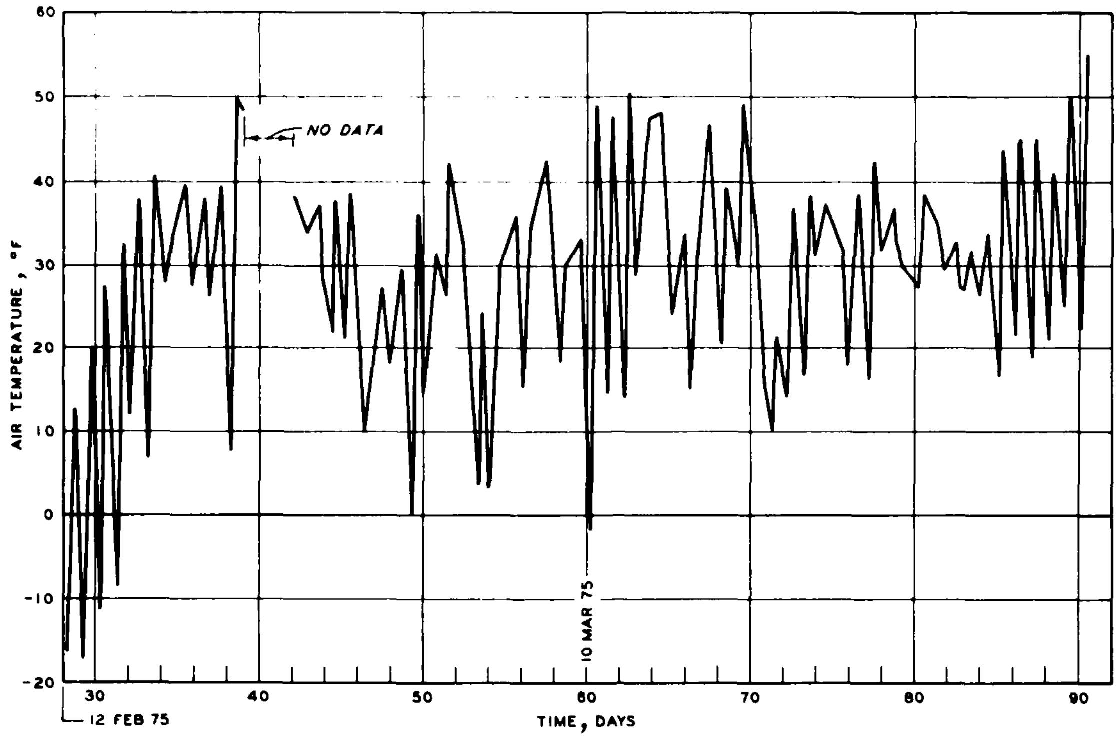

Figure 13. 90-day temperature record for ambient air during tests.

Compressive strength data (Fig. 9), for example, for cores taken from the two slabs indicate strengths less than those for the push-out specimens from these slabs (Fig. 8). It was noted that the top portion of some of the cored samples had a distinct brown color instead of the normal gray of the rest of the lower portion of the slabs. Compressive tests on the brown-colored samples showed that their average strengths were less than the gray samples. It is speculated that drilling water spilled during coring on day 14 saturated the top portion of the slabs in some areas; subsequent freezing and thawing may have weakened the top portion and caused the change in color.

Data shown in Figure 10 indicate that the flexural strengths for the two slabs are about the same after 90 days of curing, although concrete from slab 2 seemed to gain strength faster during the first 28 days. Records of air temperatures above the slabs and temperatures in the center of the slabs are shown in Figures 11 through 13.

The strength of the concrete in both slabs, as shown by the push-out and drilled cores, was 0-200 psi at day 1, 1200-1300 psi for slab 1 and 2200-2400 psi for slab 2 at day 7, and 1800-2200 psi for slab 1 and 3100-3500 psi for slab 2 at day 28.

Table 6. Result of X-ray diffraction analysis.

	RC-663(3)	RC-663(4)
$C_{11}A_7 \cdot CaF_2$	Major	Major
Anhydrite ($CaSO_4$)	Major	Major
$C_6A_xF_y$	Common	Common
MgO	Minor	Minor
Quartz	Minor+	Trace**
$CaSO_4 \cdot 1/2H_2O$	Trace	Trace
$CaSO_4 \cdot 2H_2O$	Trace	Not detected
Calcite	--	Common

\+ Or slightly less.
** Or slightly more.

Table 7. Composition of cements.

	RC-663(3)	RC-663(4)
Alite	Major	Major
Belite*	Trace	Trace
MgO	Trace+	Trace
$C_1A_7 \cdot CaF_2$	Common	Common
$CaSO_4$	Common	Common
CaO	Trace	Trace+
$CaCO_3$	Minor+	Minor+
Calcium aluminoferrite	Minor+	*A little* less than in 663(3)
Quartz	Minor**	Minor**

* Thought to be Belite.
\+ Or slightly more.
** Or slightly less.

Comparison of regulated-set cement shipments

A sample of the cement used in the field at CRREL (RC-663[4])* was brought to WES for testing to determine if the sample was different from the cement used earlier in the laboratory (RC-663[3])*. Both cements were tested with X-ray diffraction patterns (maleic acid method [Mander et al. 1974]). The results are shown in Table 6.

The detailed test results showed that RC-663(3) contained more calcium sulfate and a little more $C_{11}A_7 \cdot CaF_2$ than RC-663(4). The calcium aluminoferrite is more aluminous in RC-633(3) than in RC-663(4) but both

*WES cement serial number

Table 8. Results of chemical and physical tests.

	RC-663(3)	RC-663(4)
SiO_2 (%)	13.3	14.1
Al_2O_3 (%)	11.7	11.5
Fe_2O_3 (%)	2.4	3.3
MgO (%)	1.6	1.6
SO_3 (%)	6.5	5.2
Loss on ignition (%)	3.3	3.8
Alkalies - total as Na_2O (%)	1.21	1.27
Na_2O (%)	0.58	0.64
K_2O (%)	0.95	0.95
Insoluble residue (%)	1.09	0.75
CaO (%)	57.5	57.8
Fluoride (%)	1.13	1.09
Surface area (cm^2/g) (A.P.)	6100	6710
Specific gravity	2.99	2.99

aluminoferrites have fairly high iron contents. About the same amount is found in each cement. Table 7 compares the composition of the whole cements.

These two cements are shown to be very similar by X-ray diffraction. There seems to be a very small amount more of $C_{11}A_7{\cdot}CaF_2$ in RC-663(3), judging by the diffraction chart of the residue that is insoluble in maleic acid, but no consistent difference was found in the diffraction charts of the whole cements.

In addition to the X-ray diffraction tests, physical and chemical tests were conducted to compare the two cements. The results are shown in Table 8.

The fluoride determination was made with an Orion fluoride specification electrode. The difference suspected of being most significant between RC-663(3), which set and gained strength at low temperature, and RC-663(4), which did not, is the higher sulfate content of RC-663(3).

Tests of heat rise caused by hydration

The temperature increase of both the laboratory regulated-set cement (RC-663[3]) and the field regulated-set cement (RC-663[4]) due to hydration of the cement was determined by two different methods. The first method involved testing neat pastes of each cement (water-cement ratio of 0.5:1). The pastes were placed in insulated containers and thermocouples were inserted into the pastes for monitoring the temperature changes. The

Table 9. Temperature development (°F) in neat paste samples of both cements due to hydration.

Time (hr:min)	Laboratory cement RC-663(3)	Field cement RC-663(4)
0:00	74	74
0:05	--	76
0:10	--	86
0:15	--	122
0:22	83	132
0:25	101	136
0:30	116	141
0:40	125	146
0:50	130	152
1:00	134	156
1:15	141	164
1:30	152	173
1:45	163	181
2:00	199	200
2:15	219	218
2:30	225	227
2:45	228	225
3:00	227	223
4:00	219	215
20:00	149	140
24:00	135	128
44:00	103	99

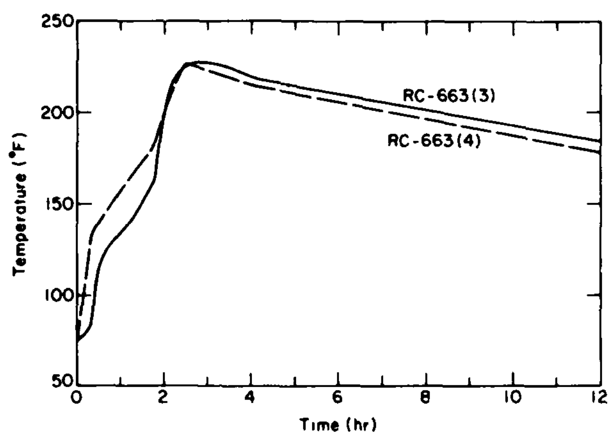

Figure 14. Temperature development in neat-paste samples of both cements due to hydration (w/c = 0.5).

Table 10. Proportions of ingredients of two concrete mixtures used to cast 2- by 2-ft by 8-in. slabs for testing hydration heat increases.

Material	Saturated surface-dry batch weights* (lb)
Cement (reg-set)	500
Fine aggregate	1265
Coarse aggregate (3/4-in. max)	1855
Water	265

* 1 yd^3.

results are shown in Table 9 and Figure 14. There was no apparent difference in the hydration heat developed.

The second method involved casting a 2- by 2-ft by 8-in. slab from each of the two concrete mixtures using aggregates from a WES source. The proportions of both mixtures were the same and are shown in Table 10. The mixtures were also air-entrained by adding 40 mL of AEA (air-entraining agent).

The only difference in the two mixtures was that one contained RC-663(3) cement while the other contained RC-663(4). The cement, water,

Table 11. Temperature development history of small slabs.

RC-663(4)*		RC-663(3)	
Time stored at 15°F (hr:min)	Temperature (°F)	Time stored at 15°F (hr:min)	Temperature (°F)
0:00	32	0:00	34
0:35	39	0:30	38
0:50	42	1:00	42
1:05	42	1:15	46
1:25	42	1:30	52
1:35	42	1:50	56
1:50	42	2:00	57
2:05	41	2:15	57
2:20	41	2:30	57
2:35	41	2:45	57
2:45	40	3:00	56
--	--	3:10	56
--	--	12:00	25
18:15	19	18:40	17
19:15	18	19:40	16
20:15	17	20:40	15

*Cement used in field test at CRREL.

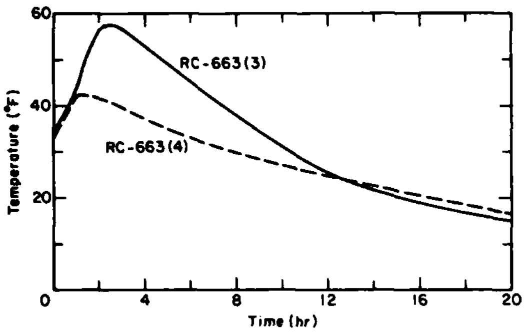

Figure 15. Temperature development in small slabs made from both cements due to heat of hydration.

mixer, molds, etc., were at 35°F prior to mixing and the aggregate was at 15°F. As soon as the test specimens were cast, a thermocouple was inserted into the center of each of the concrete slabs; they were then placed in a 15°F environment and the temperature changes were monitored. The results are shown in Table 11 and in Figure 15.

Contrary to the data obtained for temperature development in the neat pastes, there was a marked difference in the heat generated in the concrete slabs. The heat in the slab containing the cement used in the field peaked at about 15°F below that of the laboratory stock, indicating a difference in the cements. This confirmed the observations made in the field.

Strength comparisons

When the 2- by 2-ft by 8-in. slabs were cast for the temperature studies, six 6- by 6- by 6-in. cubes were cast from each of the two mixtures and placed in a 15°F environment immediately after casting. Four cubes, two from each concrete slab, were evaluated in compression tests at ages of 1, 4 and 7 days. The cubes were allowed to thaw for 2 hours at room temperature prior to testing. The results are shown in Table 12. It is apparent that the cubes made with the RC-663(4) cement froze without gaining strength. Figure 16 shows a cube from each of the mixtures after

Table 12. Strength comparisons of two samples of regulated-set cement.

Cement	slab	Compressive strength (psi) 1 day	4 day	7 day
RC-663(3) (lab)	1	1555	1475	1680
	2	1600	1600	1710
	Avg	1580	1540	1700
RC-663(4) (field)	1	46	40	56
	2	29	35	47
	Avg	38	40	52

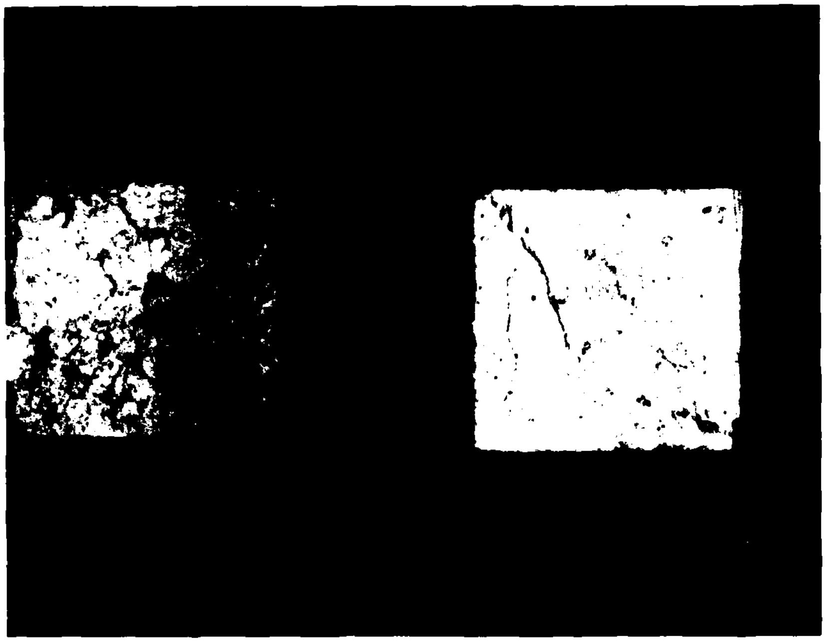

Figure 16. Compressive strength cubes made of RC-663(4) (left) and RC-663(3) (right) after test.

testing. The cube containing the cement tested at CRREL in the field appeared wet and particles of the concrete could be crumbled by hand.

The field and laboratory tests confirm that the shipment of cement used in the field tests was significantly different from the regulated-set cement used at WES for the earlier laboratory tests. It is suspected that the high water content in the concrete in the field test had a delaying effect on the setting time but other factors also contributed to a delayed set as the laboratory comparisons show. This probably can be attributed to the differences in sulfate content (6.5 for RC-663[3] and 5.2 for RC-663[4]), although this has not been definitely determined.

DISCUSSION

The prototype tests at CRREL confirmed that concrete made with regulated-set cement can be placed at mean ambient temperatures as low as 15°F and that hydration and considerable strength gain will occur. With concrete mixture temperatures at discharge of 32° and 50°F, the compressive strengths at day 28 were approximately 66% and 90 to 100%, respectively, of those for similar specimens cast and cured at 72 ± 5°F. This was even more positively demonstrated by the considerable strength gain at low tempera-

ture in spite of the unhardened mixtures being wetter than intended (5- to 8-in. slump) because of inexperience with the mixing equipment. This increased amount of moisture is known to delay the setting time of regulated-set cement at above-freezing temperatures. Also, the particular shipment of regulated-set cement used in the field experiment was not of the exact chemical composition of the earlier shipment used in the laboratory tests and did not exhibit the same setting behavior. These differences suggest a need for purchase specifications for regulated-set cement in order to ensure uniform cement behavior from lot to lot.

Because the concrete whose placement temperature was 32°F did not achieve the same level of strength at later ages as did the concrete whose placement temperature was 50°F for the same cement, the effects of placing temperature must be examined more thoroughly. Some additional concrete protection may be necessary for a short period in order to get the hydration reaction started in the cement. The necessary length of this protection time would have to be determined by additional evaluation. This time period would be dictated by how long it takes the cement paste to resist damage from the first cycle of freezing. A compressive strength of 500 psi has been suggested (ACI Committee 1973) as being the minimum strength (or maturity) the concrete should attain before it is allowed to freeze. Other required values of minimum strength have also been reported (ACI Committee 1973); however, a more exact value for this minimum must be verified. Once known, this will also dictate the earliest times at which formwork or concrete protection could be removed.

The efforts reported by Houston and Hoff (1975) and in this report have dealt solely with the use of regulated-set cement. There may be other binders, however, that can give comparable results in cold weather; these should also be identified and evaluated. These might include cold-setting polymers and a recently developed gypsum-portland cement blend called VHE cement.

RECOMMENDATIONS

In order to continue to build up sufficient supplemental background information and determine other criteria necessary for cold weather concreting and construction, it is recommended that the following tasks be undertaken.

Maturity evaluations

The American Concrete Institute (ACI) Recommended Practice for Cold Weather Concreting (ACI Committee 1973) states that concrete which has reached a compressive strength of 500 psi has had its degree of saturation reduced below a level where freezing would cause damage to the concrete. As the requirement for this critical strength value has been reported as varying from 350 to 2100 psi (Houston and Hoff 1975), this 500 psi requirement must be validated before judgments of the adequate length of protective curing can be made.

The validation should include concrete with varying proportions of [illegible] so that the influence of available moisture and concrete [illegible] can be evaluated. The evaluations should be conducted [illegible] ASTM C 671, Tentative Test Method for Critical [illegible] Concrete Specimens Subjected to Freezing. The resulting data [illegible] of a maturity concept for defining pro-[illegible]

[illegible]

[illegible] the recently developed gypsum-portland [illegible] polymers should also be examined as [illegible] set cement in cold weather [illegible] should be examined for such [illegible] times, heat development, special [illegible] needed, and cost.

[illegible] recommended practice for cold [illegible] In ACI Manual of Concrete Practice, [illegible] American Concrete Institute.

[illegible] Materials (1968) Standard method of [illegible] and sawed beams of concrete. [illegible] ASTM [illegible]

[illegible] Testing and Materials (1977) Tentative test method [illegible] of concrete specimens subjected to freezing. Philadelphia: ASTM C 671-77.

Houston, B.J. and G.C. Hoff (1975) Cold weather construction materials. Part 1: Regulated-set cement for cold weather concreting. U.S. Army Cold Regions Research and Engineering Laboratory Special Report 245.

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APPENDIX A: STRENGTH DATA

Table A1. Summary of strength data for cast cylinders, push-out cylinders, drilled cores and flexural beams.

Age at test	Curing Outdoors[a]	Curing 70°F	Temperature in center of control cyl. at time of break (°F)	Slab no.	Compressive strength (psi)	Remarks
			Cylinders cast at site (6-in. diam. by 12 in.)			
27 hr	23 hr	4 hr	47	1	9	
27 hr	23 hr	4 hr	47	1	17	
27 hr	6 hr	21 hr		1	829	
28 hr	6 hr	22 hr		1	603	
25 hr	1 hr	24 hr		2	565	
25 hr	1 hr	24 hr		2	594	
25 hr	23 hr	2 hr	36	2	11	
25 hr	23 hr	2 hr	36	2	9	
7 days	1 hr	7 days		1	2595	Cured 6 days in humid room.
7 days	1 hr	7 days		1	1610	Cured 6 days in humid room.
7 days	7 days	2 hr	41	1	580	
7 days	7 days	2 hr	41	1	595	
7 days	7 days	2 hr	41	1	1110	
7 days	1 hr	7 days		2	2740	Cured 6 days in humid room.
7 days	7 days	2 hr	45	2	525	
7 days	7 days	3 hr	49	2	720	
7 days	7 days	3 hr	49	2	665	
14 days	6 hr	14 days		1	1360	Cured 13 days in humid room;
14 days	6 hr	14 days		1	2855	top crumbled, poor cylinder.
14 days	6 hr	14 days		2	2920	
14 days	14 days	4 hr	41	1	1385	Failed at top.
14 days	14 days	4 hr	41	1	1555	Failed at top.
14 days	14 days	4 hr	41	1	1185	Failed at top.
14 days	14 days	4 hr	41	2	1225	Failed at top.
14 days	14 days	4 hr	41	2	1235	Failed at top.
			Cylinders cast at site (6-in. diam. by 12 in.)			
28 days	6 hr	28 days		1	2325	
28 days	6 hr	28 days		1	1555	Crumbled at top.
28 days	6 hr	28 days		2	3315	
28 days	28 days	4 hr	39	1	1925	
28 days	28 days	4 hr	39	1	1680	
28 days	28 days	4 hr	39	1	1580	
28 days	28 days	4 hr	43	2	1405	
28 days	28 days	4 hr	43	2	1485	
28 days	28 days	4 hr	43	2	1490	
90 days	1 hr	90 days	60+	1	2255	
90 days	1 hr	90 days	60+	1	2545	
90 days	1 hr	90 days	60+	2	2520	
90 days	90 days	4 hr	60+	1	1590	
90 days	90 days	4 hr	60+	1	1800	
90 days	90 days	4 hr	60+	1	1845	
90 days	90 days	4 hr	60+	2	1750	
90 days	90 days	4 hr	60+	2	1820	
90 days	90 days	4 hr	60+	2	1655	
92 days	92 days	2 hr	70	1	1680	
92 days	92 days	2 hr	70	1	2210	

Age at test	Curing: Outdoors[a]	Curing: 73°F	Temperature in center of control cyl. at time of break (°F)	Slab no.	Compressive strength (psi)	Remarks
92 days	92 days	2 hr	70	1	2165	
92 days	92 days	2 hr	70	1	1800	Temperature control cylinder[b].
92 days	92 days	2 hr	70	1	1620	Temperature control cylinder[b].
92 days	92 days	2 hr	70	1	2465	Corner chipped; cut to 6 by 11 in.
92 days	92 days	2 hr	70	2	1750	
92 days	92 days	2 hr	70	2	1845	Temperature control cylinder[b].
			Push-out Cylinders (4 by 6 in.)			
27 hr	23 hr	4 hr	55	1	26	Not capped.
27 hr	23 hr	4 hr	55	1	38	Not capped.
25 hr	23 hr	2 hr	36	2	24	Not capped.
25 hr	23 hr	2 hr	36	2	19	Not capped.
7 days	7 days	2 hr	44	1	1150	Voids on side of sample.
7 days	7 days	2 hr	41	1	1255	
7 days	7 days	2 hr	45	2	2400	
7 days	7 days	2 hr	47	2	2360	
14 days	14 days	5 hr	48	1	1230	Sample broke near top.
14 days	14 days	5 hr	48	1	1645	Sample broke near top.
14 days	14 days	5 hr	48	2	2840	
14 days	14 days	5 hr	48	2	3050	
28 days	28 days	5 hr	40	1	1715	
28 days	28 days	5 hr	40	1	1635	
28 days	28 days	5 hr	40	1	1710	
28 days	28 days	5 hr	41	2	3135	
28 days	28 days	5 hr	42	2	3350	
28 days	28 days	5 hr	42	2	3505	
90 days	90 days	3 hr	--	1	2180	
90 days	90 days	3 hr	--	1	1540	
90 days	90 days	3 hr	--	1	2010	
90 days	90 days	3 hr	--	2	3505	
90 days	90 days	3 hr	--	2	3720	
90 days	90 days	3 hr	--	2	2265	
			Cores (3-3/4-in. diam. by 8 in.)			
7 days	7 days	3 hr	45	1	1440	
7 days	7 days	3 hr	45	1	1265	
7 days	7 days	3 hr	45	1	1190	
7 days	7 days	2 hr	40	2	2230	
7 days	7 days	2 hr	40	2	2140	
7 days	7 days	2 hr	49	2	2170	
14 days	14 days	1 hr	34-36*	1	2025	
14 days	14 days	1 hr	34-36*	1	1810	
14 days	14 days	1 hr	34-36*	1	2160	
14 days	14 days	1 hr	34-36*	2	2925	Cored with water.
14 days	14 days	1 hr	34-36*	2	2920	Cored with water.
14 days	14 days	1 hr	34-36*	2	2790	Cored with water.
28 days	28 days	4 hr	42	1	1600	
28 days	28 days	4 hr	42	1	1665	
28 days	28 days	4 hr	42	1	1755	
29 days	29 days	1 hr	32*	2	1200	Top crumbled.

Age at test	Curing Outdoors[f]	Curing 70°F	Temperature in center of control cyl. at time of break (°F)	Slab no.	Adjusted compressive strength (psi)	Remarks[e]
29 days	29 days	1 hr	32	2	1075	Top crumbled.
29 days	29 days	1 hr	32	2	1570	Top crumbled.
30 days	30 days	10 hr	70	2	2955	Soft top sawed off; then tested.
			Cores (3-3/4-in. diam. by 8 in.)			
61 days	61 days	4 hr*	50*	1	2365	Cored with water.
61 days	61 days	4 hr*	50*	1	2480	Cored with water.
61 days	61 days	4 hr*	50*	1	1960	Cored with water.
61 days	61 days	4 hr*	50*	2	2280	Cored with water.
61 days	61 days	4 hr*	50*	2	2785	Cored with water.
61 days	61 days	4 hr*	50*	2	2205	Cored with water.
62 days	62 days	4 hr*	50*	1	1215	Cored with air at 7 days and returned to holes in sealed plastic bags until tested.
62 days	62 days	4 hr*	50*	1	1255	
62 days	62 days	4 hr*	50*	1	1610	
90 days	90 days	4 hr*	50*	1	2575	
90 days	90 days	4 hr*	50*	1	2510	
90 days	90 days	4 hr*	50*	1	2230	
90 days	90 days	4 hr*	50*	2	3455	
90 days	90 days	4 hr*	50*	2	2150	
90 days	90 days	4 hr*	50*	2	3545	
			Beams (6 by 6 by 35 in.)			
7 days	7 days	3 hr	55	1	255	
7 days	7 days	3 hr	55	1	234	
7 days	7 days	2 hr	54	2	253	
7 days	7 days	2 hr	54	2	310	
28 days	28 days	5 hr	53	1	315	
28 days	28 days	5 hr	53	1	180	Failed at old crack.
28 days	28 days	5 hr	54	2	390	
28 days	28 days	5 hr	54	2	365	
90 days	90 days	6 hr	50*	1	410	
90 days	90 days	6 hr	50*	1	360	
90 days	90 days	6 hr	50*	2	370	
90 days	90 days	6 hr	50*	2	390	

*Estimated

a. See air temperature record (Fig. 11 and 12).
b. Thermocouple embedded at center of cylinder.
c. Size correction according to ASTM C-42-68 (1968), paragraph 5.7.
d. Thermocouple temperature in center of 6- by 12-in. control cylinder.
e. Sampled cored with air as drilling fluid except where shown as cored with water.
f. Cured outside, see temperature record.

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